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Article

The Bio Steel Cycle:

7 steps to net-zero CO_2 emissions steel production

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Abstract: CO_2 emissions have been identified as the main driver for climate change, with devastating consequences for the global natural environment. The steel industry is responsible for ca. 8%-11% of global CO_2 emissions, due to high fossil-fuel and energy consumption. The onus is therefore on industry to remedy the environmental damage caused and to decarbonise production. This desk research report follows a two-tiered route: 1) exploring the Bio Steel Cycle; 2) proposing a seven-step strategy to overcome the challenges within the iron and steel industry. The true levels of CO_2 emissions in the steelmaking process, during the blast-furnace/basic-oxygen-furnace operation, will be detailed first, at 4.61t of CO_2 emissions/t of steel produced. The manuscript proposes a solution for reduced carbon emissions steelmaking with the Bio Steel Cycle components and detail on how to reach net-zero carbon emissions steel production. The 7-step-implementation-strategy as a potential solution to achieve net and true zero carbon emissions steel production in the short to medium-term. The findings of this are pointing towards the conclusion that CO_2 emissions seem to have been under-reported and under-estimated in the past, but the emission can be addressed if the correct scenarios for net-zero steel manufacturing are implemented by 2050.

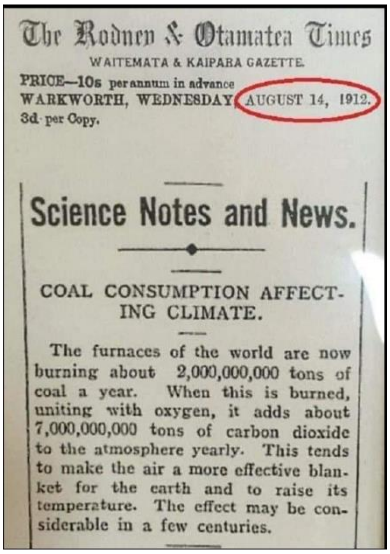
Keywords: Net-zero steel, CO_2 emissions, Bio Steel Cycle (BiSC), CAT, CCUS, Flue stack gas scrubbing

1. Introduction

The requirement to drastically reduce GHG emissions, and particularly: CO_2 emissions, has never been greater than today. The Kyoto Protocol, the Paris Agreement, and recent 2022 reports from the IPCC have clearly set out the impact which the highest ever recorded anthropogenic CO_2 emissions are having on our environment and climate. With the iron and steel industry being responsible for ca. 7%-11% of global CO_2 emissions [1,2,3,4,5,6,7,8,9,10,56,145] and China being responsible for 50% of these GHG [2], the factual level of CO_2 emissions for every t of steel produced currently stands at more than 4.6t of CO_2 emissions [11], the onus is on industry to remedy the environmental damage caused in the past two centuries [11,12,13,14,15,16]. The anthropogenic carbon emissions are at an all-time-high with reported ~65.6 Gt CO_2-equivalent in 2019 [11,12,13,14,15,16]. The 64 steel producing countries reported 1.9Gt of steel produced between January and December 2021 [17,18,19,20,21], and – based on the current findings – are likely resulting in 8,806,211,400t or ~8.8Gt CO_2-equivalent of CO_2 emissions as a result of the current linear steel manufacturing.

The importance to significantly reduce GHGs and eliminating fossil fuel combustion and usage has never been greater, and fast, practical solutions - on a global scale - are needed. Already in 1912 (Figure 1), it was recognised that coal consumption is an environmental hazard and incompatible with keeping global temperatures at a balanced level to sustain life.

Industrial processes have for more than two hundred years polluted the air we breathe, and already in 1912 this was recognized, as this Australian newspaper clip will demonstrate in Figure 1:



The Rodney & Otamatea Times
WAITEMATA & KAIPARA GAZETTE.
PRICE—10s per annum in advance
WARKWORTH, WEDNESDAY, AUGUST 14, 1912.
3d per Copy.

Science Notes and News.

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COAL CONSUMPTION AFFECTING CLIMATE.

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

Figure 1: *The Rodney & Otamatea Times – Waitemata & Kaipaba Gazette, Science Notes & News (1912)* [22]

It is worth pointing out that in this article, merely the in-furnace-coal-combustion process is mentioned in connection with carbon emissions. CO_2 emissions from energy consumption, mining, pelletising, coking, sintering, steel smelting, casting, rolling, annealing, rolling, finish machining and surface treatment and related processes have not been considered at that time. But as these authors more than hundred years ago already established – possibly based on the carbon content of coal (78-95%) [5,23,24] and the release of CO_2 into the atmosphere by combustion, the factor to be 3.5: 7,000,000,000/CO_2 emissions/2,000,000,000t of steel, resulting in 3.5t of CO_2 emissions in the blast furnace operations per tonnes of steel alone, by 1912. Although the steelmaking process has undergone significant improvements and the BOF operation has allegedly reduced the CO_2 emissions to between 2.2t and 1.6t/CO_2/t of steel produced - it begs the questions why this knowledge has not been used to establish the true CO_2 emissions over the past 2 centuries?

The current state of the decarbonisation of the iron and steel industry has been carefully reviewed and key publications have been identified. A direction-giving quality can be attributed to Bataille et al.'s (2018/2021) publications [25,26], as this provided key components to develop the BiSC model and strategy and set the foundations to establish the seven steps to net-zero carbon steelmaking. Invaluable insights were provided with regards to decarbonisation of the iron and steel industry, "green" steel in particular and the mechanisms and processes necessary to achieve sustainable and carbon free iron and steel production. Setting the scene, Muslemani et al. (2021)[27] worked on identifying the opportunities and challenges for decarbonizing steel production by creating markets for "green" steel products. Their in-depth investigation provides valuable insight into potential markets for green steel products and their manufacturers and to make the economic case for sustainable production. Arens, Åhman, Vogl (2021) [28] researched which countries are factually prepared to "green" their coal-based steel industry with electricity and reviewed respective climate and energy policy. They subsequently published policy guidance by country for "green" steelmaking. One of the key papers to provide the technical insight into the vital components of sustainable steel is Wang et al.'s (2022) and Wang's (2022)[29,30] investigations of the opportunities for technology-driven decarbonisation and green steel for Australia. They carried out economic modelling of a green steel value chain with wider implications for the second and third tier small to medium enterprises and heavy industry. Models, pathways, and roadmaps are guiding the industry on the path to decarbonisation, and therefore Bataille, Nilsson, Jotzo's (2021)[26] study was considered a key paper. They provided some components for the BiSC (Bio Steel Cycle) model [10] when they looked at the iron and steel industry in a net-zero emissions world. They identified new mitigation pathways, new supply chains, modelling needs and policy implications. Their mitigation pathways investigation towards decarbonisation of steelmaking provided invaluable analysis and insight into supply chains and policy needs. Liu et al.'s (2022) and Liu et al.'s (2020) [31,32] work created a technological roadmap towards optimal decarbonisation development of China's iron and steel industry. They developed policy guidance exploring the deep decarbonisation pathways. Richardson-Barlow et al. (2022) [33] identified policy and pricing barriers to steel industry decarbonisation during their case study of the UK iron and steel industry. They issued a guidance paper, exploring the decarbonisation pathways. One of the paths towards decarbonisation of the iron and steel industry is using hydrogen, and particularly: hydrogen direct reduction. The discussion around H_2 has gained more momentum again and Öhman, Karakaya, Urban (2021) [34] researched the transition potential into a fossil-free steel sector and identified the necessary conditions for technology transfer to hydrogen-based steelmaking in Europe. Toktarova et al. (2020) [35] investigated the low-carbon steel industry-interactions between the H_2DR of steel and the electricity system via a Swedish case study. Toktarova (2021) [36] created a cost-optimal design of the steel-making industry and electricity system with close to '0' CO_2 and were another key paper towards the creation of the BiSC model. Matino and Colla (2021) [37] took a slightly different approach when they endeavoured to issue a guidance paper and overview of the state of the art, recent developments, and future trends regarding hydrogen route for a green steel making process. In their opinion, steel production based on hydrogen is one of the key factors to improve the carbon footprint of the steel industry. A more global perspective was taken by García-Herrero, Tagliapietra, Vorsatz (2021) [38], within their development of hydrogen development strategies. They see hydrogen as a candidate to fully decarbonise the European steel making, global aviation and maritime transport. Grasa et al. (2022) [39] investigated the blast furnace gas decarbonisation through calcium assisted steel-mill off-gas hydrogen production. They took an experimental and modelling approach to the calcium assisted steel-mill off-gas H_2 production process (CASOH) in integrated steel making plants. Devlin and Yang (2022) [40], however, focused more on regional issues when researching supply chain implications and their potential for decarbonising steel. Their focus was energy efficiency and green premium mitigation, green hydrogen-based iron ore reduction and renewable electricity-based steelmaking. Case studies, such as Gosens, Turnbull, Jotzo's (2021) [41]work concentrated on a highly granular model of China's coal production, transport, and consumption system. Their work shows how its decarbonization and energy security plans will affect coal production and the effect of decarbonisation on coal imports. Griffin and Hammond (2019/2021) [42,43], however, cast the net wider with the focus on global transitions and investigation into making UK steel production more environmentally benign whilst advancing decarbonisation of the iron and steel sector. Lu et al.'s (2022) [44], also provided insight into China`s iron and steel industry decarbonisation options, based on a 3-dimensional analysis. Whereas Steenbrink (2022) [45] focused on the impact of the Carbon Border Adjustment Mechanism. They conducted an economic and geopolitical assessment of the German-Chinese aluminium trade flows. Their paper provides a thorough assessment on how best to incentivise non-EU trade partners to adopt measures comparable to the EU's and - simultaneously - yielding revenue to reuse in accelerating decarbonisation of steelmaking. In terms of carbon avoidance, capture and utilisation, Kempken et al. (2021) [46] identified possible decarbonisation barriers (Deliverable 1.5). The isolation of major barriers to the decarbonisation process of the EU iron and steel industry provides valuable insights into the reasons why the industry seems quite reluctant to decarbonise their existing production and facilities. Williams et al. (2021) [47] conducted a case study, during which they focused on CO_2 capture and storage (CCS) and presented the results of focus group discussions in a Welsh steel-making community. The topic of decarbonisation of steel production by switching to renewable sources was welcomed during the local focus group discussions and showed widespread support in the community for the company's efforts in this direction. Tanzer, Blok, Ramirez (2021) [48] went one step further by focusing their research on integration of biomass when they investigated the decarbonisation opportunities via BECCS: promising sectors, challenges, and techno-economic limits of negative emissions and BECCS in the iron and steel industry. Sarić, Dijkstra, Van Delft (2021) [49] considered CO_2 abatement in the steel industry through carbon recycle and electrification by means of advanced polymer membranes. For this, a conceptual process design and assessment was performed for a process that is a combination of carbon recycling and electrification of the steel making process. Wang (2022) [30] focused more on energy saving technologies and optimisation of energy use for a decarbonised iron and steel industry. A valuable guidance paper was issued where suitable decarbonisation technologies are categorised. A different approach was taken by Singh et al. (2022) [50], as they researched the opportunities of decarbonisation of steel mill gases in an energy-neutral chemical looping process, providing the technical elements for carbon enrichment for plant stimulation (CEPS), which is based on flue stack gas scrubbing. In addition to CAT, CCUS and BECCS, waste recycling is a vital part of the decarbonisation process. Jacob, Sergeev, Müller (2021) [51] provided a thorough review when they investigated the potential of valorisation of waste materials for high temperature thermal storage. An overview of the decarbonisation process of both the electricity and steel making industry. Sun (2022) [52] seemed to have worked along the same lines and developed a concept for the decarbonisation of the iron and steel sector for a 2° C target, using inherent waste streams. Furthermore, other aspects of decarbonisation needed to be considered, as Antonazzo et al. (2021) [53] pointed out: a key component of the transition process to decarbonisation is the need to meeting green skills needs for a sustainable steel industry. They Identified the skills required for a steel industry in transition to sustainability. Zhiming et al. (2021) [54] researched material-based decarbonisation implications and how lime quality affected metallurgical steel quality and the value in use of lime in the BOF steelmaking process. Garvey, Norman and Barrett's (2022) [55], however, focused on technology and material efficiency scenarios for net zero emissions in the UK steel sector. Their assessment included steel plant retrofitting and grid electricity decarbonisation.

The objectives of this multi-disciplinary and multi-industry-overarching study are to identify the most efficient implementation opportunities of the chosen processes and technologies to reduce the current BF-BOF route 4.6t CO_2 emissions / t of steel produced to factual '0', ordered in seven easy steps, from short-term to long-term solution implementation.

2. Materials and Methods

The research used global steel data and literature on sustainability, decarbonisation and CAT, CCS and CCUS technology. The main reason underpinning this choice and course of research is that, as suggested by the Steel Yearbook 2018/2019 [17,19] the global iron and steel industry is still heavily reliant on coal and is responsible for between 7% and 11% of global CO_2 emissions [1,2,3,4,5,6,7,8,9,10,56] and China being responsible for 50% of these GHG [2].

The impact of different technologies [35] on the processes at all stages in the steelmaking process [43], decarbonisation of the iron and steel manufacturing [1,2,3,4,5,6,7,8,9,10,17,18,19,20,21,23-55], and related databases and corresponding literature [1-145] were investigated – including literature with regards to CAT, CCS and CCUS and the circular economy, sustainability and decarbonisation of the steel industry were categorised for ease of implementation, from easy to more challenging and depending on duration.

An Excel database was used for data collection, modelling and key calculations. The parameters were defined as t of CO_2 per t of steel produced, although further parameters for future research are being allowed. The research works with metric tonnes only. Formulae were developed and adjusted [57,58,119], as follows:

1) $CO_2E_{total} = \sum \text{(emissions per ton of steel)} \times \Omega \text{(output tons produced)}$

2) 1 charge (400 tons in 40 minutes)

$$CO_2E_{total,1c} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_{2Smelt} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \times (CapBF \times t)$$

3) 1 day (10,000 tons max.)

$$CO_2E_{total,1d} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_{2Smelt} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \times 10{,}000$$

4) 30 days/1 month (10,000 tons x 30 days)

$$CO_2E_{total,1m} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_{2Smelt} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \times 300{,}000$$

5) 1 year (p.a.) (300,000 x 12)

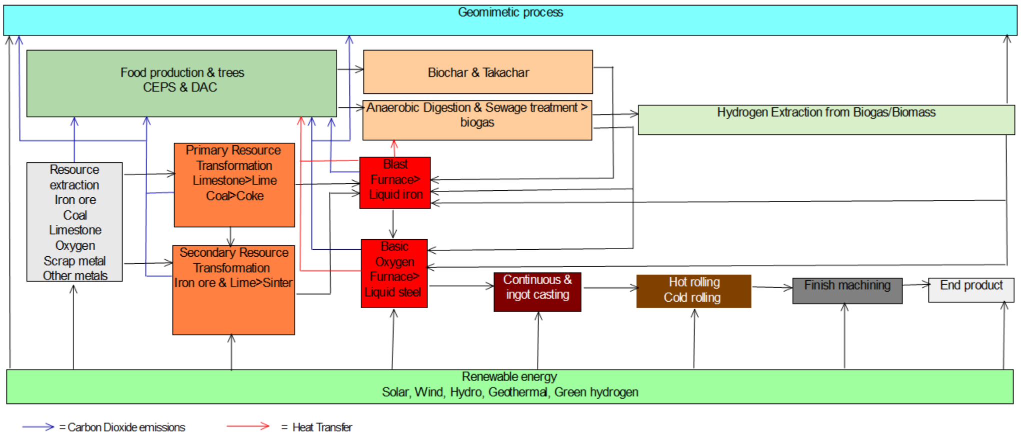
$$CO_2E_{total,p.a.} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_{2Smelt} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \times 3{,}600{,}000$$

CO_2E_{total} = Total CO_2 emissions
CO_2RE_{coal} = CO_2 emissions resource extraction coal
CO_2RE_{ore} = CO_2 emissions resource extraction iron ore
CO_2RE_{oxy} = CO_2 emissions resource extraction oxygen
CO_2PT_{coal} = CO_2 emissions primary resource transformation coal > coke
CO_2PT_{lime} = CO_2 emissions primary resource transformation limestone > lime
CO_2ST_{sint} = CO_2 emissions secondary resource transformation coke & iron ore > sinter
CO_{2Smelt} = CO_2 emissions smelting
CO_2BF = CO_2 emissions blast furnace
CO_2BOF = CO_2 emissions basic oxygen furnace
CO_2C = CO_2 emissions casting
CO_2M = CO_2 emissions milling
CO_2FM = CO_2 emissions finish machining
CapBF = Capacity blast furnace / basic oxygen furnace
t = time (charges per day) 400 tonnes per charge every 40 minutes, Ø of 10,000 tonnes/day

In order to determine the BF/BOF-route CO_2 emissions, the formula had to be adjusted, accordingly, to:

$$6)\ CO_2E_{total} = \sum(CO_2BF + CO_2BOF)$$

Additionally, engineering simulation software has been used, such as Simul8 and Aspen Plus V11. The Simul8 and Aspen Plus V11 models are being adjusted continuously to meet the different applications of carbon avoidance, carbon saving, and carbon utilisation technologies, in accordance with the strategy flowchart in Figure 2:



Legend:

Green	Renewable or natural energy generation at ambient temperature
Medium green	Food production, hydrogen, biomass, CEPS and DAC
Blue	Geomimetic® process 100% carbon utilisation
Orange	Energy intensive resource transformation >1400°C
Red	BF/BOF operation highest energy consumption and heat generation >1700 °C
Dark brown	Casting 1520°C
Brown	Hot-Cold rolling and drawing: > 1200°C

Figure 2: *Strategy flowchart Simul8 steel linear production configuration* *

*The colour-coding within Figure 1 is identical to the master database (Excel), which has been created to gather and display findings, facts and figures, and is supposed to signify the energy intensity and heat development at the different stages of the steelmaking process in °C.

3. The Bio Steel Cycle components and 7-steps principles

The conventional linear steel manufacturing process, including all processes such as coal, iron ore and limestone extraction, crushing, pelletising, sintering, smelting, casting, rolling, and finish machining have been investigated and resulted in establishing that the BF/BOF-route alone produces ~4.6t of CO_2 emissions, which are one of the undesired by-products of every metric t of steel produced. The results to date of research into the CO_2 emissions at the various stages of the steelmaking process and related sub-processes have been established, and the findings of the BF/BOF-route are displayed in appendix 5. CO_2 emissions as a direct result of steel manufacture increased by 1.6% or 8.7 Gt CO_2 in 2020, although in the Net-Zero-Emissions-by-2050 scenario, industry emissions are estimated to decrease by 2.3% annually at 6.9 Gt CO_2 by 2030 – despite expected industrial production growth [4]. Improved material and energy efficiency, the increased utilisation of renewable energy technologies, and development and deployment of low-carbon process routes (including CCS and hydrogen) are considered to have an emission-reduction-effect of individually between 12 and 30%. Fossil-fuel derived energy generation, and combustion of fossil fuels for transport - including aviation - are the two biggest sources of CO_2 emissions - worldwide [3-5,13,35,56,59]. Steel production is in close third place, followed by cement production and chemical and glass industry [3-5,13,35,56,59].

One possible solution to combat this issue is the Bio-Steel Cycle (BiSC) as a model, based on circular tech economical principle. Steel scrap is considered a resource, and similar to recycling waste and by-products, is an integral part of the circular production process. Off-gases (CO_2 and other GHG) are being captured and reutilised, and alongside implementation of steelmaking process improvements, furnace heat capture and utilisation, CAT, CCS, and CCUS technologies and processes, and multi-disciplinary external components, are closing the circle [14,15,25,26,35,59,60].

Suitable literature was thoroughly investigated with regards to applied and innovative steelmaking procedures, CAT, CCS and CCUS processes, and improved management systems such as I4.0 [61,62].

Most likely scenarios have been considered, and the principles of the Bio Steel Cycle model are applicable to most heavy industries: such as cement, chemical, glass, paper, and transport. It includes using renewable energy technologies, avoiding CO_2 emissions by incorporating process improvement technologies, recycling waste and by-products and capturing post-combustion emissions where possible [14,15,25,26,35,59,60], as displayed in Figure 3:

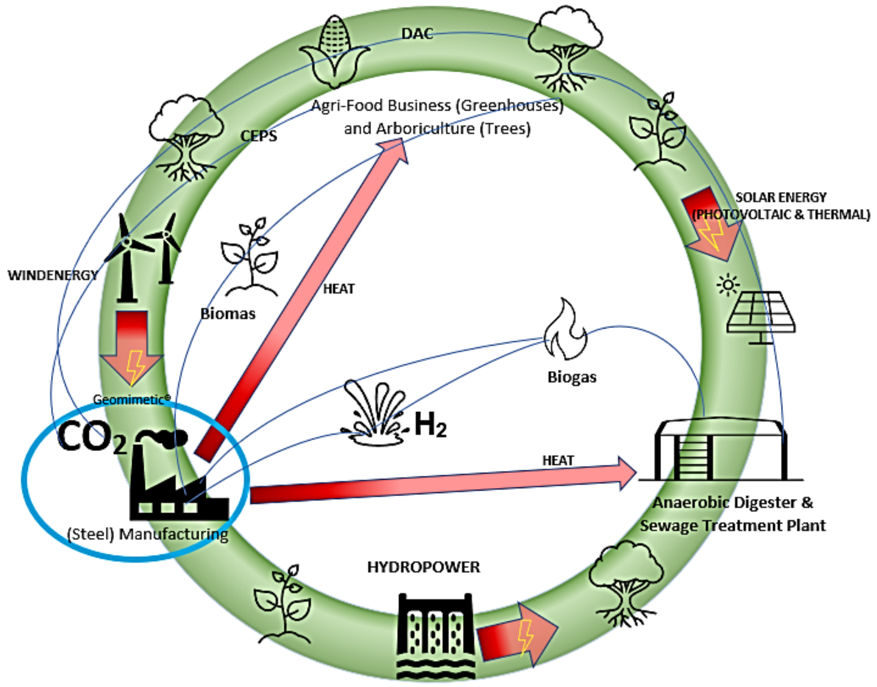


Figure 3: *The Bio Steel Cycle concept and cyclical resource utilisation flow*

Analyses of the technical and economical long-term potential of novel steel production technologies CAT, CCS and CCUS and in the UK [63-66], Germany [67] and beyond used techno-economic models to model three research-stage [35,43,59,64] ore-based steelmaking routes versus BF-BOF-route [68]. It was concluded, that in comparison, the BF with CCS1 (BFCCS) [6-9, 67], hydrogen direct reduction (H-DR) [6-9], and iron ore electrolysis (EW) [35,36], energy and raw material efficiency is significantly higher for H-DR and EW [6-9, 67-70] and the 80%-reduction-target by 2050 [71] was thought to be perfectly achievable in the scenario, as per Tata Steel's Zeremis vision much sooner, by

2045 [72]. It was found that there are a sufficient number of viable CAT, CCS and CCUS technologies, methods and strategies at TRL7-9 available for immediate BiSC implementation and achieving short- to medium term significant reduction of CO_2 emissions in steelmaking. The urgency for sufficient prioritisation throughout all industries and political willingness (subsidies) cannot be emphasised enough [14,15,71] – the need to create a viable commercial environment, due to the required high capital investment and a significant dependency on electricity prices [35,56,73,74].

The following key components within the Bio Steel Cycle are based on a circular production process and are functioning in an interactive manner. The basis for this system is the BF/BOF route and involves the afore mentioned CAT, CCS and CCUS and process improvements where possible. Innovative technologies such as Hisarna [70] and GrInHy [75] and hydrogen direct reduction (HDR) have CO_2 saving potential in their own right, as explained in more detail, as follows. Removing coal as primary energy source or using hydrogen direct reduction, an immediate 30% CO2 emissions reduction is possible and therefore [31,35,64,76-78], replacing coal with biomass or hydrogen would reduce the CO_2 emissions from steel making potentially by the same percentage. According to Siemens (2022) [79], a 50% carbon emissions reduction is immediately possible via utilisation of green hydrogen direct reduction. The standard steel production (SSP) process in combination with the currently operational newly developed technologies [35,69,70,72] also achieve a reduction of more than 50% with successive implementation to less than three metric tonnes /t of steel produced. By incorporating the BiSC components of CAT, CCS and CCUS into existing steel production sites, an almost 100% CO_2 emission reduction can be achieved, immediately.

The post-combustion capture of CO_2 (CCS) and other GHGs and the exploration of carbon scrubbing of flue gases have been explored. There are several possible technologies and processes to be considered for post-combustion carbon capture [25,26,43,59,80]:

- mechanical capture
- compression and dehydration
- membrane installation
- guiding off-gas through troughs of physical solvents/solid sorbents (such as Zeolite13X) and chemical solvents
- as well as utilising metal-/organic frameworks,

Renewable energy technologies are one of the key components within the Bio Steel Cycle, as CO_2 emissions in steelmaking can be reduced by more than 30% [81], if commercial entities in iron and steel production [25,26,82] were to simply switch their energy provider [59] to those which supply energy which was derived using 100% renewable energy technology and producing their own energy by retrofitting their plants with renewable energy technologies (wind, solar PV). The same applies to greenhouses, as there is a vast amount of roof space available, which has to date not been utilised. The static requirements would obviously have to be considered, but as the cost and weight of solar energy and solar PV has decreased significantly over recent years (Dastoor, 2021) [92] to less than £3/m2 and to a foil body in appearance, it can be considered an unmissable opportunity.

In the spirit of innovative, multi-disciplinary approaches to solving contemporary CO_2 emission issues, the positive effects of DAC (Direct Air Capture) and utilisation of woodlands for carbon capture cannot be emphasised enough. As one of the critical components of the BiSC, woodlands/trees for DAC would even be a profitable side-line for steel producers, as illustrated in the following Figure 4:

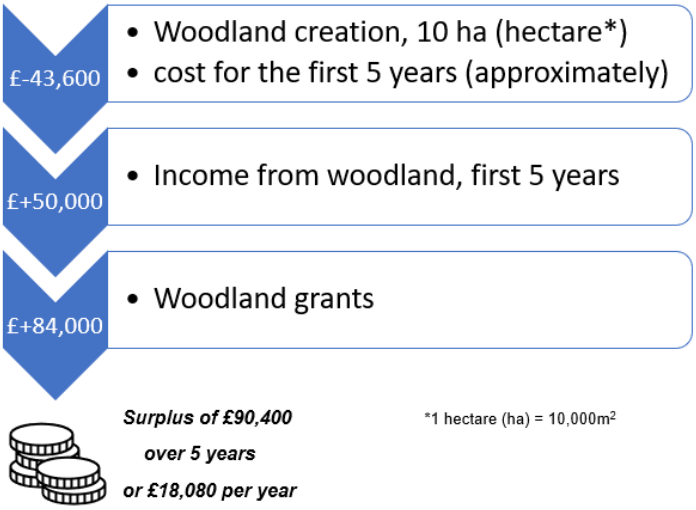


Figure 4: *Woodland creation graph*

Trees and vegetation as natural carbon sinks should ideally be planted around steel production plants to absorb the remaining CO_2 emissions via direct air capture (DAC) [83-85]. Whilst at the same time, the plant matter could feed the anaerobic digester, biochar plants or directly used at selected quality in iron and steelmaking as readily available biomass. In this respect, bamboo beats deciduous native plants with its carbon sequestration capacities: on average, one hectare of bamboo stand absorbs ~17 tonnes of carbon per year [86]. Native deciduous and non-deciduous trees have a carbon sequestration capacity of on average 9t of CO_2/ha of tree plantation [6-9,83-85]. Planting a sufficient number of trees should be considered in the planning for the updating of existing steel production plants and for any new development in order to meet the UK governments zero emissions targets. The UK tree cover stands at 13.2% (3.2 million ha, 66.65m people = 0.048 ha per capita) [83,84], which is the lowest in the Northern hemisphere. In comparison, forests and wooded land cover over 182 million hectares in the EU, which is about 42% of the EU's total land area. This equates to 0.36 hectares of forest per capita in the EU in comparison [6]. Woodlands not only capture post-combustion CO_2 and create biomass for anaerobic digestion, but they also may create recreation and employment opportunities and additional sources of commercial activity. Additionally, they offer a low-cost opportunity for carbon-offsetting, which could be seen as a commercial opportunity in itself.

Food production - in greenhouses - anaerobic digestion, and sewage treatment plants require a stable ambient temperature throughout the year, which requires a conventional source of heating. Re-using heat from the steelmaking process, the expenditure of installing heating systems and using fuel and energy is simply not required, as the air has already been heated. Although the installation of a suitable infrastructure would have to be considered, the economical case has to be further investigated, and the financial viability – cost of ducts and pipework against the installation of a heating and cooling system including energy requirements - needs to be solid to make a case for re-utilising flue-stack off-heat. The flue-stack heat can be as high as 1650°C and would have to cool down, i.e., via travelling through adequately sized pipework, ducts and possibly turbines (which in their own right would possibly be able to generate electricity, via convection, baffle systems or plate-heat-exchangers). The energy saved on heating food production facilities is deserving of further investigation, as this will effectively contribute to achieving net-zero carbon emissions in steel production.

Additionally, incorporating the CEPS (Carbon Enrichment for Plant Stimulation) process into the BiSC based circular steelmaking process [30,80], involves CCUS by means of driving CO_2-enriched flue-stack off-gas from combustion processes into CEPS units. Subsequently, this at almost 100% carbon enriched air, is then directed into greenhouses to stimulate plant growth. The chosen CEPS model is deemed scalable and has the capacity to provide 85 tonnes of CO_2 p.a. in its current configuration [80]: concentrating CO_2 from ambient air (400 ppm) into an enriched product stream at 1000 ppm CO_2. Locating the source of CO_2, i.e., flue gases from production in steel, cement [87] or energy production and greenhouses in close proximity of each other eliminates costs associated with filtering, deactivation, compression, transportation, handling, distribution, and storage entirely. Every successfully installed CEPS unit/greenhouse infrastructure is effectively a CO_2 sequestration station and the economic feasibility is based on 1 kWh = 3600 kWs = 3.6 MJ [88], costs between £0.11 – £0.21/kWh and 17.8kJ/mol CO_2 = 17.8kJ/44g CO_2 [89,90] for pure CO_2 versus 8.5kJ/mol CO_2 = 8.5kJ/44g CO_2 for enriched, 1000ppm CO_2, costing effectively between \$15 and \$309/t CO_2. The efficiency, technical and economic viability are making the case for temperature swing absorption/desorption flue gas carbon capture.

The anaerobic digester and sewage treatment facility are vital components within in the BiSC and would be ideally integrated into the steel mill or quite possibly be independent businesses in their own right, conveniently located on site of the steel production facility. These units would be able to accommodate debris from nearby woodland management and additional biomass from surrounding residential and commercial entities. Steelmaking by-products, such as brown water, can be treated at the sewage treatment facility. The cleared sewage can subsequently be utilised to fertilise the food production units. The anaerobic digestion process in itself produces biogas, which can be used in steel production, but it also provides the base for extraction of hydrogen. The green hydrogen produced at or nearby the anaerobic digestion facility can then be used in (steel) production within the hydrogen direct reduction (HDR) process. As this has been derived from biogas as a result of anaerobic digestions, this can therefore be considered green hydrogen. Hydrogen direct reduction (HDR) has been piloted over recent years and has shown to have great CO_2 avoidance potential, and green hydrogen technologies are currently developed by a number of significant industry leaders, such as Mannesmann Salzgitter [75], in cooperation with the European Commission and Tata Steel. Green HDR in blast furnace and electric arc furnace application is considered as having a significant impact on reducing CO_2 emissions in steel manufacturing, as this process uses 3.48 MWh of electricity per ton of steel product and emits only 2.8% of blast furnace CO_2. However, as the prices of fossil-fuel derived energy have increased significantly, it is imperative to replace fossil-fuel derived energy with renewable energy technologies and biomass [35,36]. Technologies such as ReclaMet (Waste resource recovery, post-combustion) [69] electrolysis projects i.e., GrInHy and H2Future [6-9,75] (direct water splitting: biomass>hydrogen, pre-combustion) all have an impact in the magnitude of between 12% and 25%, although further research is required to establish not only the most effective technology in terms of environmental impact, but also which technology can be deployed the fastest and the most cost-efficient.

A further key component of the BiSC is the Geomimetic® process [91], as these units are effectively recycling facilities for the recycling of reclaimed concrete and the reutilisation of CO_2, filters, dust, sludge, and slack from (steel) production. These units have the capacity to reduce post-combustion CO_2 emission to effectively zero and should be on site of any (steel) production plant. The workings of the Geomimetic® process are in its essence carbon utilisation and sequestration processes at the same time, as these recycle CO_2 from flue gases and recycled concrete into synthetic limestone and aggregate in cement production, with the potential of absorbing 100% of the CO_2 emissions produced. This is a technique suitable to be applied in any industrial production setting: energy, steel, concrete, chemical industry, glass industry, paper, and transport, to name a few.

4. The 7 steps to net-zero carbon emission steel manufacturing

The newly introduced concept "Bio Steel Cycle" (BiSC) [10] provided the elements with which a net-zero carbon emissions steel production can be made a reality, in the short-term. The following key components within the Bio Steel Cycle are based on a circular production process and are functioning in an interactive manner. The basis for this system is the BF/BOF route and involves the afore mentioned CAT, CCS and CCUS and process improvements where possible. Innovative technologies such as Hisarna and GrInHy and hydrogen direct reduction (HDR) have CO_2 saving potential in their own right. Removing coal as primary energy source or using hydrogen direct reduction, an immediate 30% CO_2 emissions reduction is possible [31,35,64,76-78], and therefore, replacing coal with biomass or hydrogen would reduce the CO_2 emissions from steel making potentially by the same percentage. According to Siemens (2022) [79], a 50% carbon emissions reduction is immediately possible via utilisation of green hydrogen direct reduction. The standard steel production (SSP) process in combination with the currently operational newly developed technologies can also achieve a reduction of more than 50% with successive implementation to less than 3 metric tonnes per ton of steel produced. By incorporating the BiSC components of CAT, CCS and CCUS into existing steel production sites, an almost 100% CO_2 emission reduction can be achieved, immediately.

The post-combustion capture of CO_2 (CCS) and other GHGs and the exploration of carbon scrubbing of flue gases have been explored. There are several possible technologies and processes to be considered for post-combustion carbon capture have been considered [25,26,42,43,59,80]:

- mechanical capture
- compression and dehydration
- membrane installation
- off-gas flow through physical solvents/solid sorbents (such as Zeolite13X) troughs and chemical solvents
- as well as utilising metal-/organic frameworks

Renewable energy technologies are one of the key components within the Bio Steel Cycle, as CO_2 emissions in steelmaking can be reduced by more than 30% [81], if commercial entities in iron and steel production [25,26,82] were to simply switch their energy provider [59] to those which supply energy which was derived using 100% renewable energy technology and producing their own energy by retrofitting their plants with renewable energy technologies (wind, solar PV). The same applies to greenhouses, as there is a vast amount of roof space available, which has to date not been utilised. The static requirements would obviously have to be considered, but as the cost of solar energy and solar PV has decreased significantly over recent years [92] to less than £3/m2, it can be considered an unmissable opportunity. Figure 5 demonstrates the steps, built on the components within the BiSC, which should be taken with the aim to net-zero carbon emission steel production.

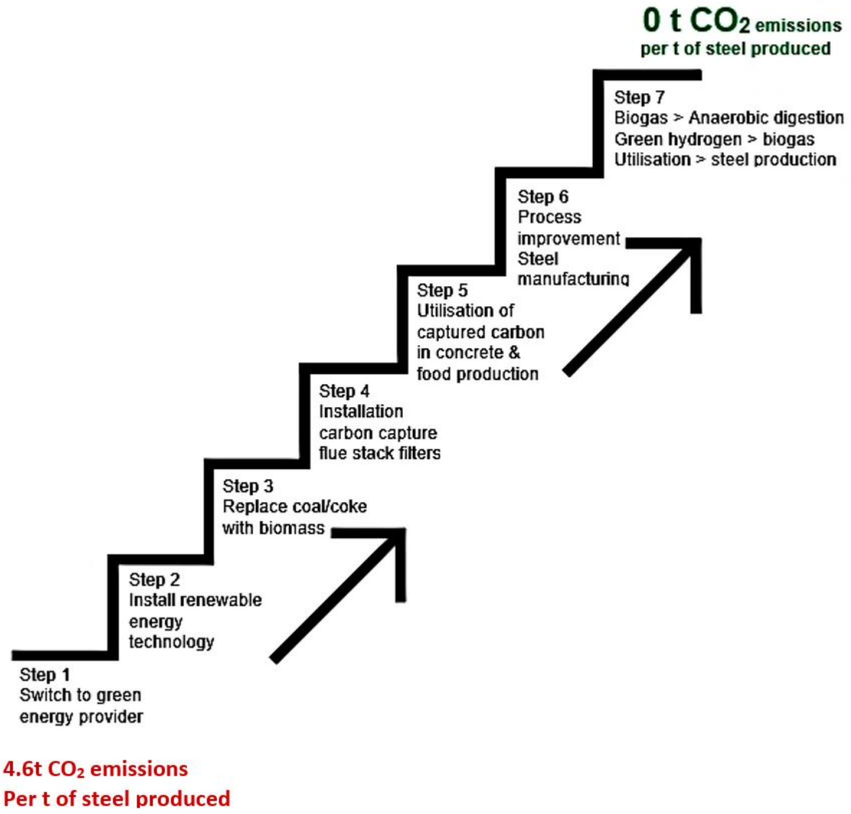


Figure 5: *The seven steps to achieving net-zero carbon emissions steel production*

The steps 1-7 were introduced based on the level of ease of implementation and from short-term to long-term project duration, starting with step one by switching energy providers and arriving at step seven with producing biogas as a result of full implementation of all elements of the Bio Steel Cycle (BiSC), splitting green hydrogen from this biogas and using thus gained hydrogen in steel manufacturing for hydrogen direct reduction (HDR).

There are a range of energy providers, which claim to produce energy exclusively based on renewable energy technologies. The image Figure 6 demonstrates the flow of the seven steps in some detail:

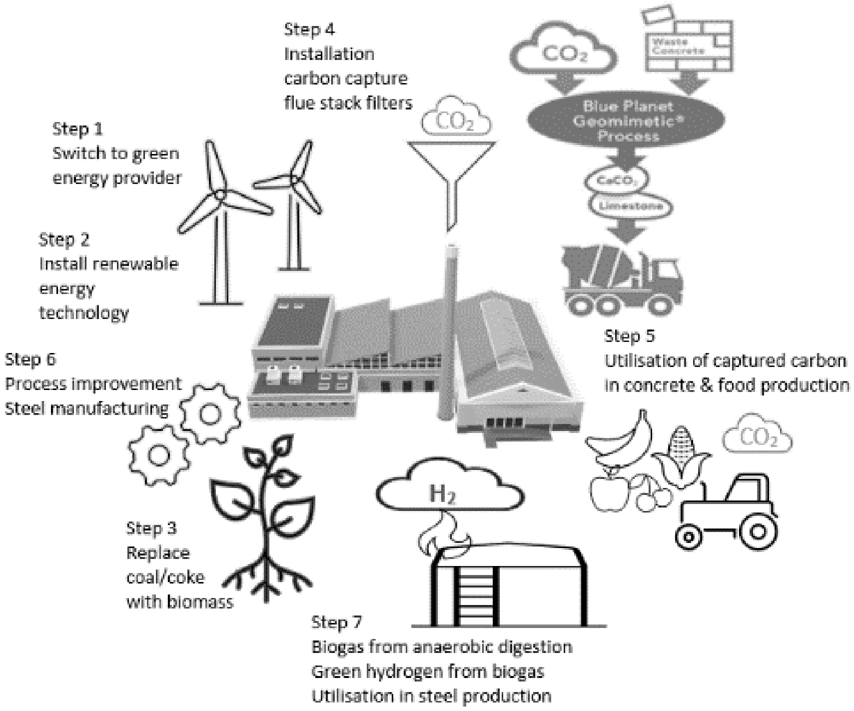


Figure 6: *The seven steps to net-zero steel production*

Step 1 – Switching to green energy provider is probably the easiest to achieve. Any steel producer will just have to make an informed choice to switch their energy contract to an energy provider who produces energy solely relying on renewable energy technologies, and not – as it has been up to now – the companies who agree the best deal, regardless of the consequences for the environment.

Step 2 - Installing renewable energy technology. This requires surveying of existing steel plants, regarding static performance of buildings, ground parameters and structures in situ. Selection of the most suitable product from a range of technologies and producers is the most time-consuming step after surveying the locations.

Toktarova et al. (2020) [35] identified a 30% CO_2 emissions savings potential by replacing fossil-fuel derived electricity with renewable energy derived. Most industrial structures well maintained under British Standards are suitable to accommodate the installation of the mature technology solar energy panels, either as solar thermal (hot water production) or photovoltaic panels (PV) (electricity). There are such a very wide range of solar and PV systems available, that it would be beyond the scope of this paper to list these in their entirety. It may suffice at this point to mention that there are suitable systems available for every type of setting, from on-roof, over to in-roof and wall-covering solar panels and even foils, which can be retrofitted to provide a reliable source of energy all year round. Even windows may consist of solar panels, as the newest known development are semi-transparent solar-cells. Researchers at the University of Michigan have developed a technique to manufacture highly efficient, semi-transparent solar cells at scale, which use micron-scale electrical connections between individual cells which constitute the solar modules [93].

Wind energy pylons are – besides solar – another effective way to produce electricity from a natural source (wind). This technology is mature and widely used, Again, there

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are a wide range of products on the market and the site parameters will determine which system would be suitable for the location in question.

At sites where solar or wind energy systems are unsuitable, open- and closed-loop hydro energy systems might have their place to provide energy for industrial processes. In the US, this technology is widely used, where creating closed-loop systems using pairs of existing or artificial lakes or reservoirs instead of rivers would avoid the need for new dams. There are currently projects underway, where in Bell County, Kentucky, for example, an old coal strip mine is being re-used [94]. As Wales in the UK has a vast array of those locations, it should be practical to install these. Figure 7 will provide some details (not to scale) to the principles of this technology:

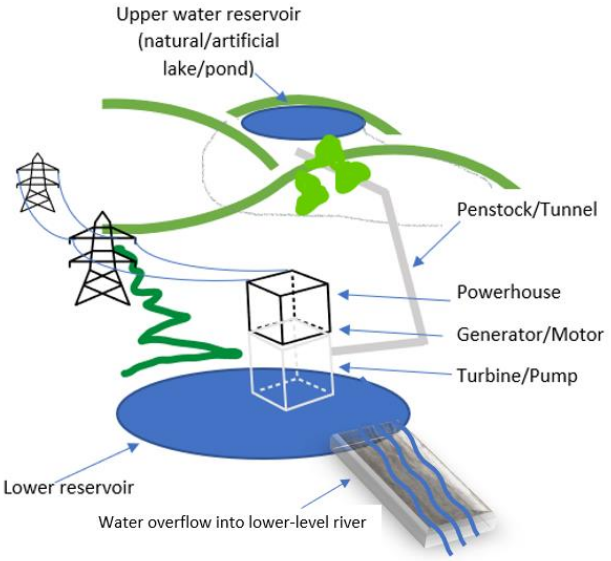


Figure 7: *Pumped-storage hydropower, open loop*

Step 3 - Replacing coal & coke with biomass. Coal and energy derived from combustion of fossil fuels is the biggest emitter of CO_2 emissions [2] and replacing coal with biomass in steel production would quite easily achieve a 30% reduction in carbon emissions, which is the reason why renewable energy technologies and replacing coal & coke with biomass are cornerstones in the Bio Steel Cycle. Replacing pre-combustion fossil fuels with biomass [6-9,35,59,67,95] and operating (green) hydrogen direct reduction (HDR) as well as capturing post-combustion CO_2 emissions with the Geomimetic ® process [91] are efforts which have the potential to reduce the CO_2 emissions in steel production to almost '0'. There is considerable outreach into other industries, such as the application of the Geomimetic® [91] process, which produces aggregates from CO_2 emissions and recycled concrete to producing new concrete and utilisation of BOF slacks for road building.

Step 4 – Installation of carbon capture flue stack filters (CCUS). These technologies are wide ranging, and every production site has their own parameters and challenges to overcome. Thorough surveying of the sites and greenhouse gas emission (GHG) points need to be identified, and depending on the situation, a suitable GHG capturing system can be installed.

Step 5 - Utilisation of captured carbon in concrete & food production. Blue Planet [91] are using the so-called "Geomimetic® process", where recycled concrete and captured carbon are being reformed to make new concrete and aggregate. In combination with manufacturing post combustion flue stack carbon capture, the utilisation of the thus captured carbon and subsequent utilisation in making new concrete (carbon sequestration). This process has the capability to reduce the carbon emissions from steel production by almost 100%.

Step 6 - Process improvement in steel manufacturing. Greater material and energy efficiency, and deployment of low-carbon process routes are all critical. The steel production process has been thoroughly investigated in every aspect from mining to recycling and it can be said that there is currently a global effort underway for developing more environmentally-friendly and resource-saving technologies in steel production, such as TGRBF (top gas recycling blast furnace operation, coal mine methane recovery [25,26,35,60,64-66,69,70,72,96] and HISARNA [20,69,70,78,89,90,95,97], which eliminates the need for the sintering process entirely. HISARNA, implemented individually, has the potential to reduce CO_2 emissions from steel production by at least 30%.

Step 7 - Biogas from anaerobic digestion - Green hydrogen from biogas - Utilisation in steel production. Trees are natural carbon sinks [83-85], and ideally, woodlands would be planted around steel production plants to absorb the remaining CO_2 emissions via direct air capture (DAC) – while simultaneously, the trees would provide some of the material for producing biochar and organic matter to be fed into the anaerobic digester, alongside agricultural businesses.

Planting a sufficient number of trees [6-9,83-85] and both anaerobic digester and biochar plants [6-9] are vital components within the Bio Steel Cycle and instrumental to meet the UK governments zero emissions target. They should be considered in the planning for the updating of existing steel production plants and for any new steel plant development or refurbishment. As the UK tree cover stands at 13.2% (3.2 million ha, 66.65m people = 0.048 ha per capita) [83,84], it is fair to say that this is the lowest percentage in the Northern hemisphere. EU forests and wooded land cover over 182 million hectares (42%) of the EU's total land area [83,84].

Biochar [98] can easily be used as a direct replacement for coke or coal. Biogas & biomass also as alternative to commercial gases and fossil fuels [6-9,35,62,81], as their properties allow for 1:1 replacement. Using biochar instead of coke in (steel) production could reduce the CO_2 emissions by 30%.

Additionally, “green” hydrogen extraction from biogas, naturally produced by anaerobic digestion, offers additional carbon avoidance opportunities. Hydrogen direct reduction (HDR) has been piloted over recent years and has shown to have great CO_2 avoidance potential (Green hydrogen technologies are currently developed by a number of significant industry leaders, such as Mannesmann Salzgitter [75], in cooperation with the European Commission and others [6-9]. Green hydrogen implies hydrogen production using energy from renewable resources only, which is where the Bio Steel Cycle comes to full circle: biomass from trees used for DAC is converted to biogas in the anaerobic digester, which produces biogas. The hydrogen is then extracted from the biogas, using renewable energy technologies exclusively.

5. Results and Discussion

The results of this study are the identified levels of CO_2 emissions during the BF/BOF-route in steelmaking, as per table 1:

Table 1: *CO_2 emissions BF/BOF-route*

Step in production		SEC* CO_2	CO_2	Author
		- t/t product -		
Blast furnace		0.288	2.1	[31,42,43,112,125]
Basic oxygen f.		0.018	2.2	[31,43,55,76,125]
Total	∑	0.306	4.3	
Total	∑		4.606	Total t/CO_2/t steel produced

*SEC = Specific Energy Consumption

The sum total of identified levels of CO_2 emissions at ~4.61/CO_2/t steel is the result of thorough investigation of research into every process step along the linear steelmaking BF/BOF route, to date.

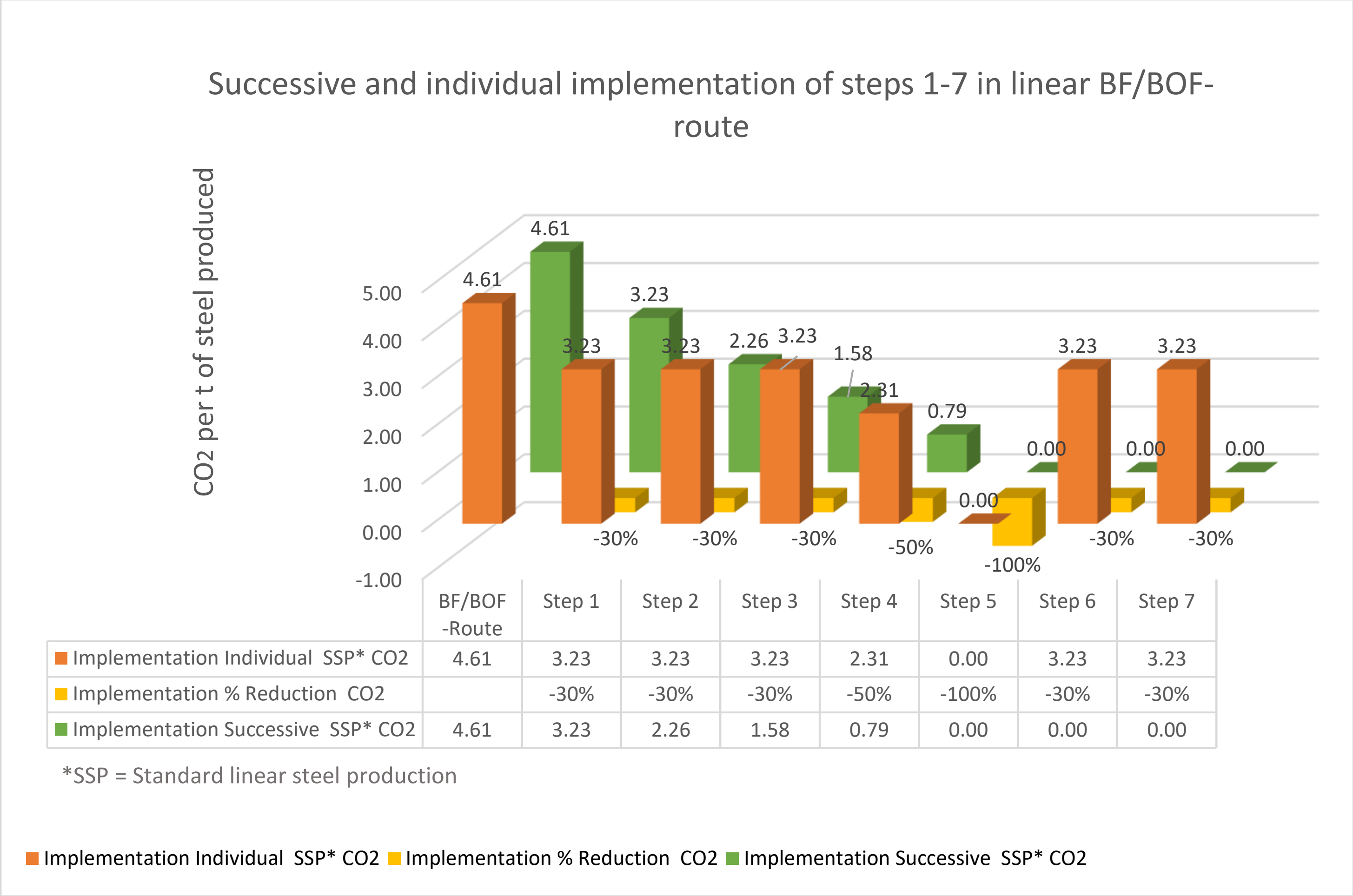
The individual seven steps towards ‘0’ carbon steel production have a different effect, based on the way they are being implemented: either individually or in sequence (successive), as displayed in table 2 and Figure 8:

Table 2: *Individual/successive implementation of the seven steps to 0 carbon steel*

Implementation	Individual SSP* CO_2	% Reduction CO_2	Successive SSP* CO_2
BF/BOF-Route	4.61	-	4.61
Step 1	3.23	-30%	3.23
Step 2	3.23	-30%	2.26
Step 3	3.23	-30%	1.58
Step 4	2.31	-50%	0.79
Step 5	0.00	-100%	0.00
Step 6	3.23	-30%	0.00
Step 7	3.23	-30%	0.00

(*Standard Steel Production)

Notably, during the sequential implementation of the seven steps to ‘0’ carbon steel production - already with step 5 - 100% carbon reduction has been achieved.



	BF/BOF -Route	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
🟧 Implementation Individual SSP* CO2	4.61	3.23	3.23	3.23	2.31	0.00	3.23	3.23
🟨 Implementation % Reduction CO2		-30%	-30%	-30%	-50%	-100%	-30%	-30%
🟩 Implementation Successive SSP* CO2	4.61	3.23	2.26	1.58	0.79	0.00	0.00	0.00

Figure 8: *Individual and successive implementation of steps 1-7*

This would logically render steps six and seven obsolete, with successive implementation, but the technical application of flue stack scrubbing technology, processes or material is quite challenging, and the efficiency is dependent on site factors and the quality of the installation, as well as the execution.

The industrialisation processes have for more than two hundred years caused significant damage to the natural environment. Although the current UK government seems to have abandoned their commitments to reducing carbon emissions in the UK and are instead issuing licences for natural gas exploration (Shell/Jackdaw)[99], and new coal mines (Cumbria)[100], industry seems to have understood the severity of the climate crisis we find ourselves in. In 2018, Tata Steel announced a partnership with chemicals company Nourvon with the aim of producing hydrogen and oxygen at Tata Steel Europe B.V.’s Ijmuiden plant in the Netherlands. Using water electrolysis, this effort is part of the company's drive to be a carbon-neutral steel manufacturer by 2050. As they are using electricity generated by using renewable energy technologies, the plant is set to save up to 350,000 t/p.a. of CO_2. The aim is to use the hydrogen as a reductant in the direct reduced iron steelmaking process [70]. Tata Steel have requested financial support to the tune of £1,5bn to fund its transition to greener production from the UK government for investing in sustainable technologies at their Port Talbot (Wales/UK) plant, which employs more than 4,000 people at present [72]. With the 2020 UK Government "UK Green Industrial Revolution" paper still fresh in everyone's mind[101], this might possibly come to pass.

Industry leaders have already recognised that the current linear steel production process is detrimental for our environment, and they have taken already considerable action by investing in R&D into production process improvement and infrastructure improvement towards sustainable and carbon-neutral steel production. The governments in the respective countries might be inclined within their "green" agendas to award green loans at favourable terms to enable businesses to reach their sustainability goals sooner rather than later. Legal frameworks require adaptation to accommodate an attractive solution for businesses – in the form of tax incentives and subsidies, possibly re-directed from nuclear & fossil fuel subsidies – and to apportion a set percentage of gross profits to drastically change their business models to sustainable, circular production processes. Despite global pressure, making steel – even in the UK – is still a very attractive business and it can be done sustainably.

Previous afore mentioned studies have focused on the assessment of policy needs, skills needs, supply chain pressures on a regional and global scale, and the requirement for models, strategies and guidance papers and investigated the technical solutions for the decarbonisation of the iron and steel industry. This paper is the first of its kind to a) assess sustainability guidelines, b) technical progress and viability of technical and process solutions for CAT and CCUS, c) identify the factual CO_2 emissions of the BF/BOF-route of steelmaking, and c) offer a multi-disciplinary model and strategy to achieve factual '0' carbon emissions steel manufacturing in one research report.

Successive implementation of the BiSC components and process improvements and following the "7 steps to net-zero carbon emissions steel production" are quite possibly the mechanisms which are set to achieve between 50% and 100% CO_2 emissions reduction, immediately.

The author's interest has been focused on the decarbonisation of the steel industry and further investigation of the CO_2 emissions along the whole steel making process, starting with coal and iron ore extraction, is currently under way.

6. Conclusions

The 7 steps to net-zero carbon emissions steel production and the Bio Steel Cycle components are providing a feasible strategy to reach net-zero carbon emissions steel production in the short- to medium-term. The BiSC seven steps to take for reaching net-zero/factual-zero carbon emission steel production seem to be technically possible and practically implementable in the short-term. The global anthropogenic ~65.6Gt CO2-equivalent emissions in 2019, reported by the 64 steel producing countries and documented 1.9Gt of steel produced between January and December 2021, are set to be resulting in 8.8Gt CO2-equivalent of CO_2 emissions. This volume as the product of the current linear steel manufacturing process leads to the conclusion that the iron and steel industry's emissions might have possibly in the past been heavily underestimated and underreported.

Industry leaders have already recognised that the current linear steel production process is detrimental for our environment, and they have taken considerable action by investing in R&D into production process improvement and infrastructure improvement towards sustainable and carbon-neutral steel production. The governments in the respective countries might be inclined within their "green" agendas to award green loans at favourable terms to enable businesses to reach their sustainability goals sooner rather than later. Legal frameworks require adaptation to accommodate an attractive solution for businesses – in the form of tax incentives and subsidies, possibly re-directed from nuclear & fossil fuel subsidies – and to apportion a set percentage of gross profits to drastically change their business models to sustainable, circular production processes.

Despite global pressure, making steel – even in the UK – is still a very attractive business and it can be done sustainably. This research has proposed a sustainable solution to avoid and remove carbon emissions from steel industry by implementing the Bio Steel Cycle in seven steps to achieve net-zero steelmaking, latest by 2050. A road map needs to be prepared to show the correct direction and required actions for government, policy makers, and steel manufacturers.

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Compliance with Ethical Standards

To ensure objectivity and transparency in research and to ensure that accepted principles of ethical and professional conduct have been followed, the authors herewith declare that this research has been self-funded and there are no conflicts of interest. Informed consent has been given by individuals providing qualitative data.

Data Availability Statement:

“Not applicable”

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